Porosity Effects on Low-k Dielectric Film Strength and Interfacial Adhesion

Grant M. Kloster, Tracey Scherban, Guanghai Xu,
Jeanette Blaine, Brad Sun, Ying Zhou
Intel Corporation
Logic Technology Development
Hillsboro, Oregon 97124

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Outline

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2. Four-Point Bend
3. E-beam
4. E-beam Mechanism
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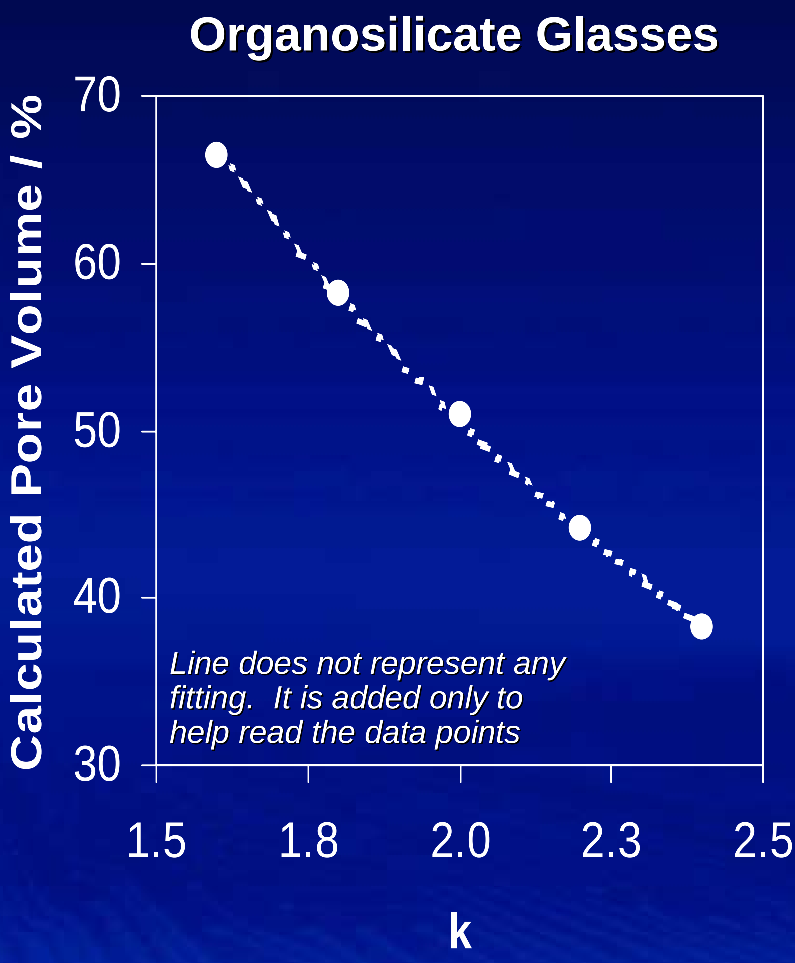
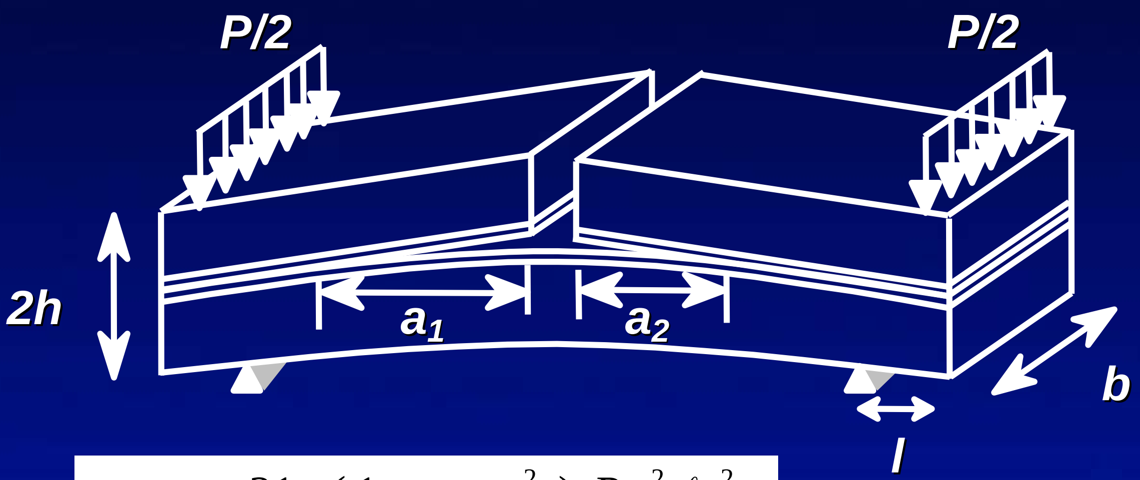
Motivation: Improved Mechanical Properties



- **Porosity needed to achieve low k**
  - **Modulus/Hardness decrease**
  - **Adhesion trend for porous ILD unknown**
    - Increase by surface roughness?
    - Decrease by crack initiation points?
    - Increase by arresting cracks?
- **Need E > 6 GPa and Gc > 5 J/m² to survive CMP and packaging***
- **Goals**
  - Establish effect of porosity on adhesion
  - Assess e-beam for improving the mechanical strength of organosilicates

*Reference – Scherban, T., Sun, B., Blaine, J., Block, B., Jin, B., Andideh, E., *IITC Conf. Proc.*, **2001**, 257-259.

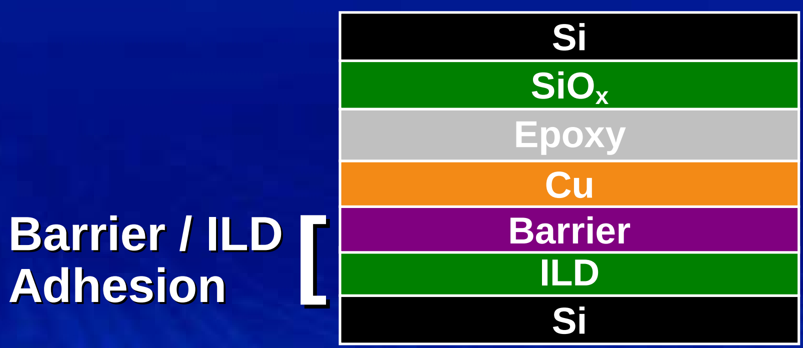
Four Point Bend Measurement

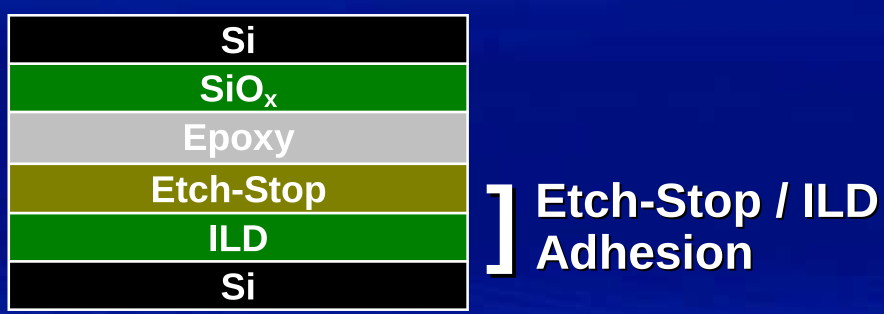


- Blanket film stack epoxied to a Si backing – uniform epoxy key to reproducibility
- Pre-crack initiated in Si substrate followed by bending in a four-point flexure configuration
- Crack propagates to and along the weakest interface

$$G = \frac{21(1-\nu^2)P^2\ell^2}{16Eb^2h^3}$$

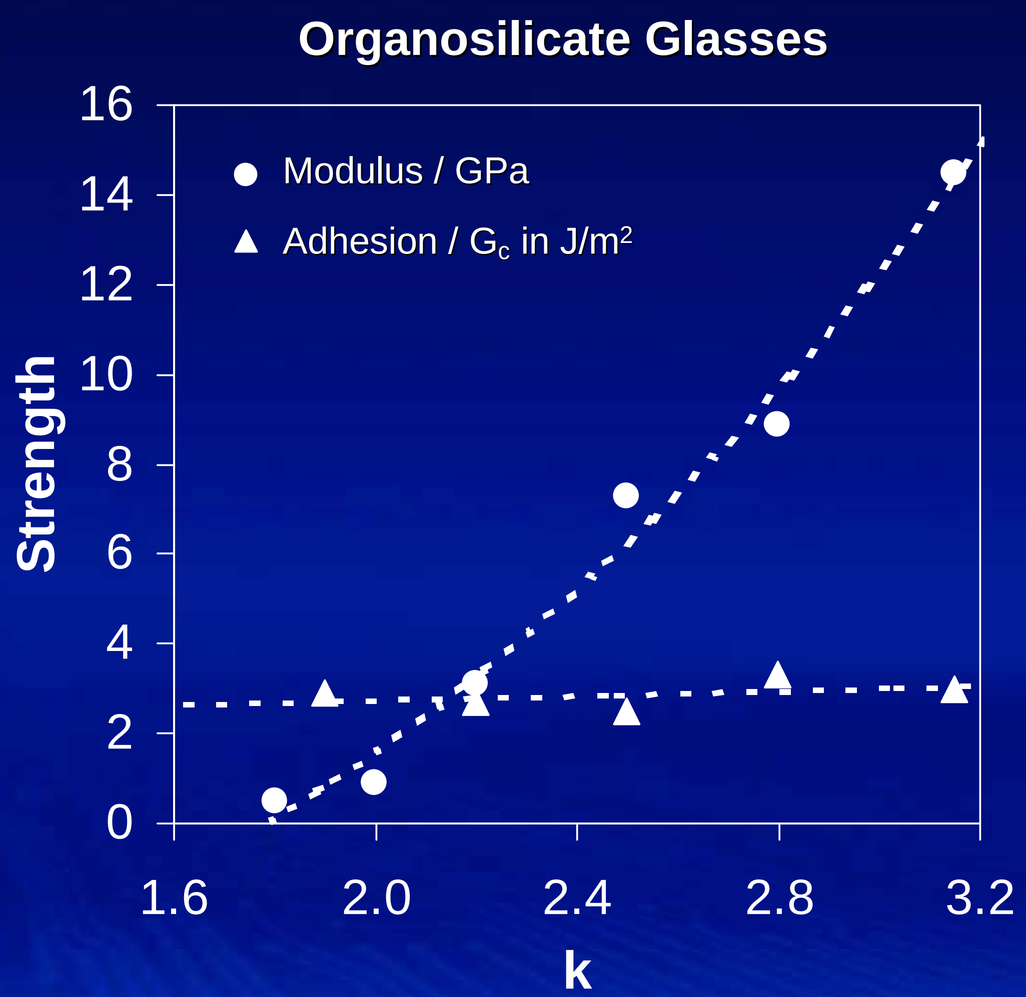
Equation to calculate Fracture Energy





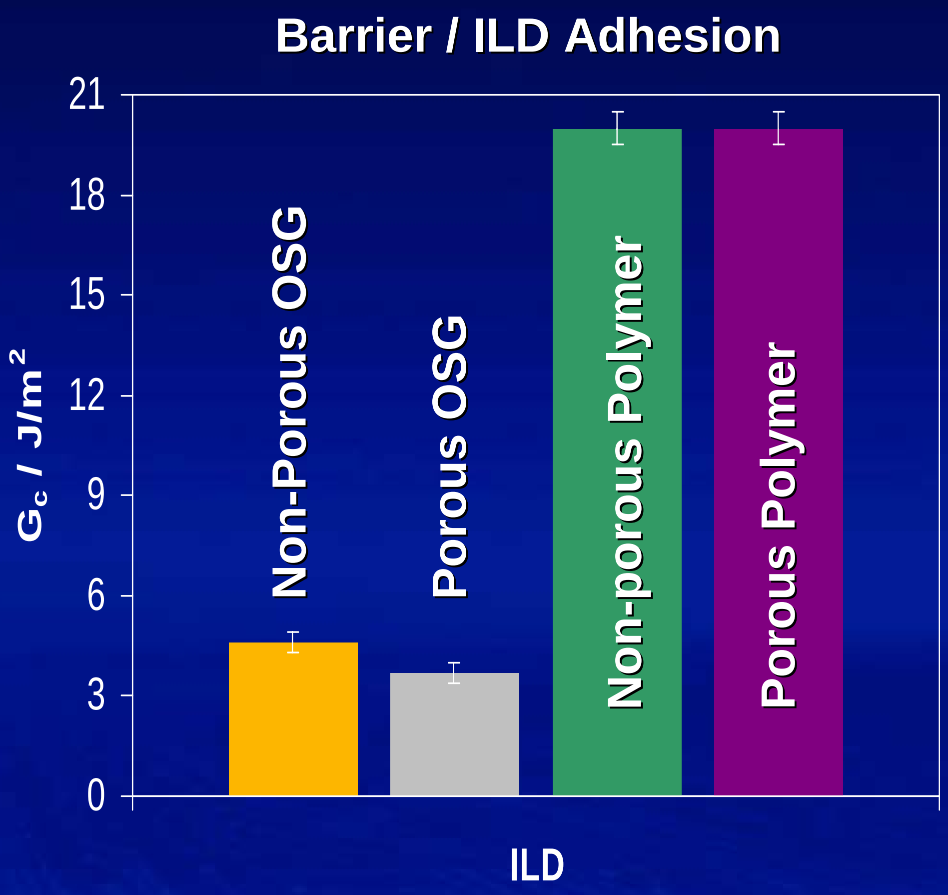
Reference – Ma, Q., *J. Mat. Res.*, 12, **1997**, 840-845.

OSG / Etch-Stop Adhesion vs. Porosity



- Etch-stop adhesion to OSG is not degraded by porosity
- Adhesion may be modulated by other factors such as interfacial chemistry
- Modulus trend is consistent with previously collected data

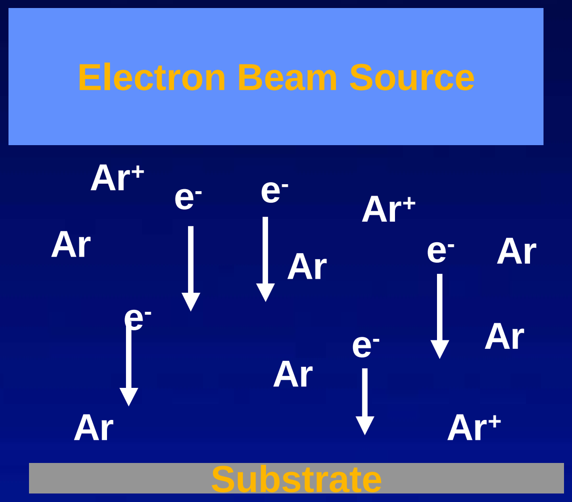
Barrier Adhesion



- Barrier adhesion also is unaffected by porosity
- Adhesion of OSG < polymer for porous and non-porous ILD's

Improved Bulk Modulus of OSG by E-beam

- E-beam showed the most improvement and the least k impact for post-cures surveyed
  - Large improvement (5X – 7X) in E & H
  - Small (10-20%) impact to k
  - Sacrifice some k value
  - Empirically, E α cohesive strength



• Vary depth by V_{acc}, Vary energy by dose

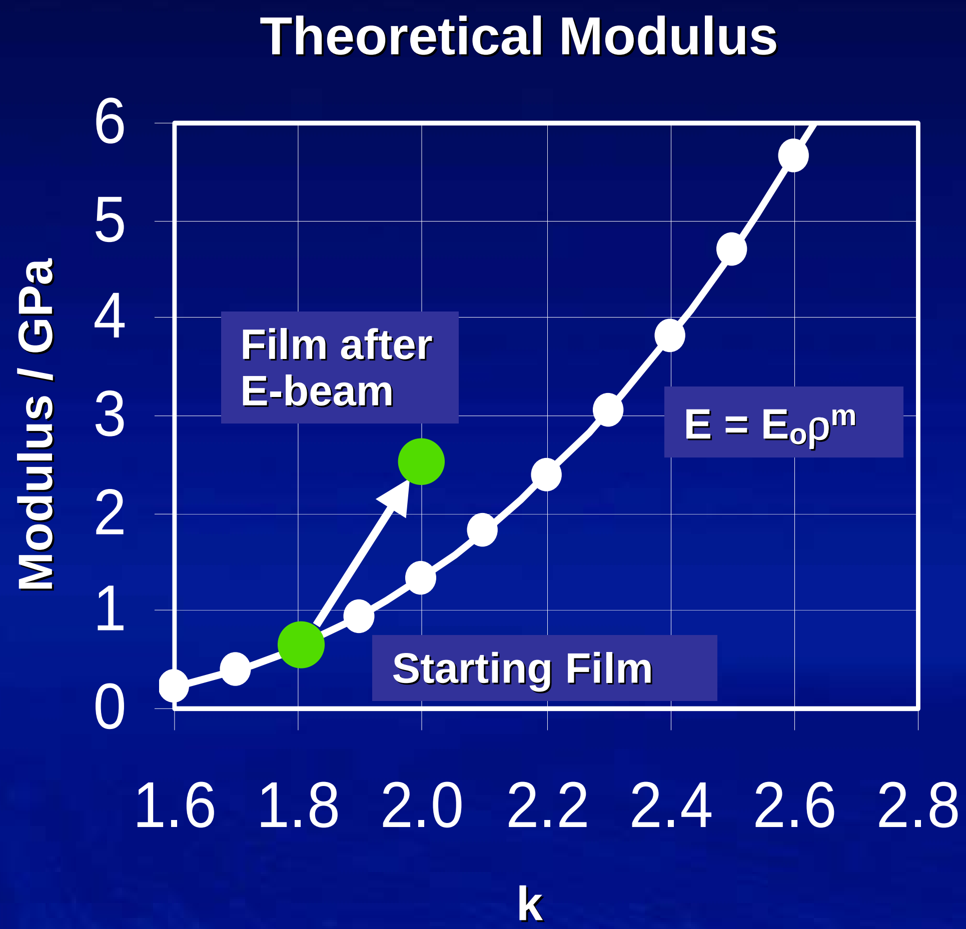
OSG Mechanical Properties Before & After E-beam

Treatment	k	E (GPa)	H (GPa)	G_c* (J/m²)
No E-beam	1.8	0.5	0.1	3.7 ± 0.1
Low Dose	2.0	2.4	0.3	4.1 ± 0.2
High Dose	2.2	3.7	0.4	3.6 ± 0.6

** Gc is for adhesion to an etch-stop*

Porous OSG Type Materials

Possible Ways to Increase the Modulus



	k	E (GPa)
No Treatment	1.8	0.5
E-beam	2.0	2.4

- **Ways to increase modulus**
  - Decrease porosity
  - Increase base material modulus (structural change)
- **Porosity decrease does not account for all of the modulus increase**

Reference – Ma, H., Roberts, A., Prévost, J., Rémi, J., Scherer, G., *J. Non-Cryst. Solids*, 277, **2000**, 127-141.

Fundamental E-beam Questions

- What is the mechanism that significantly increases modulus with only a slight impact to k?
  - ☞ Does the Si-OH concentration change?
  - ☞ Does the porosity or pore size change?
  - ☞ Does the carbon content change?

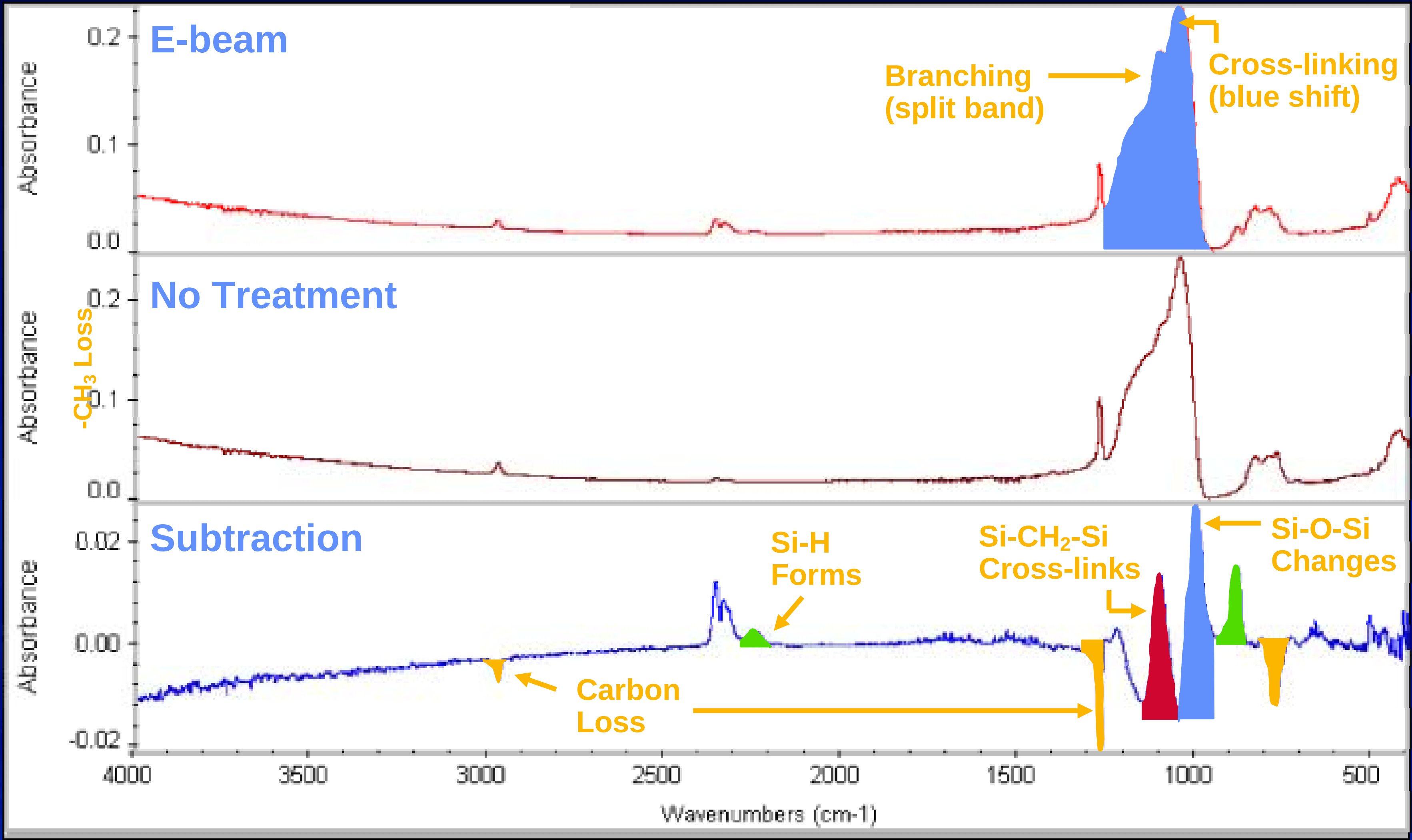
Pore Size and Porosity after Treatment

Organosilicate Glass

	PALS		EP	
	d (nm)	Connectivity	d (nm)	Porosity
No treatment	2.5	Open	3.0	40
E-beam	2.5	Open	3.0	41

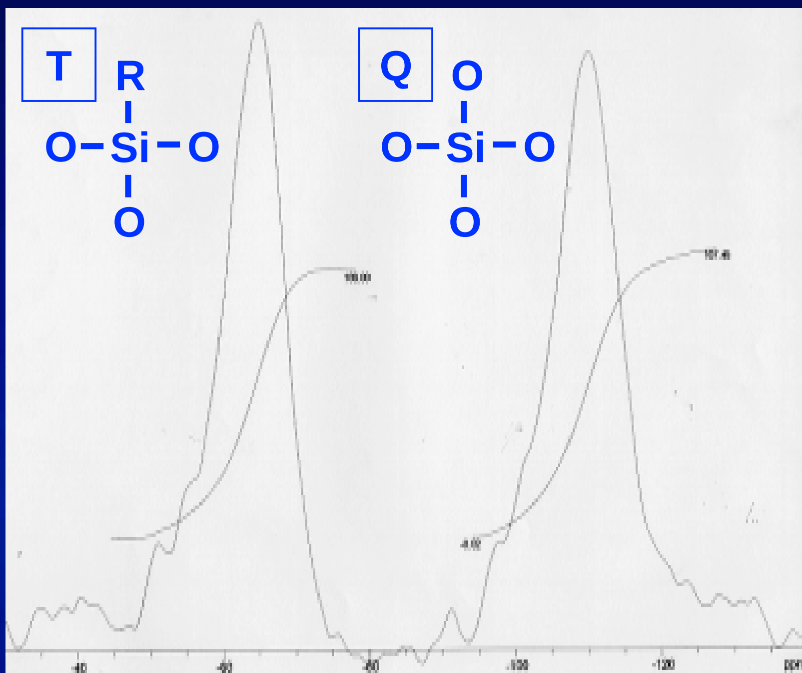
- No change in pore size even though film shrinks 5-10%
- Residual stress increases 15-20%
- Supports increased cross-linking in the micro-porous region (d < 10A)

FTIR - Structural Changes after E-beam

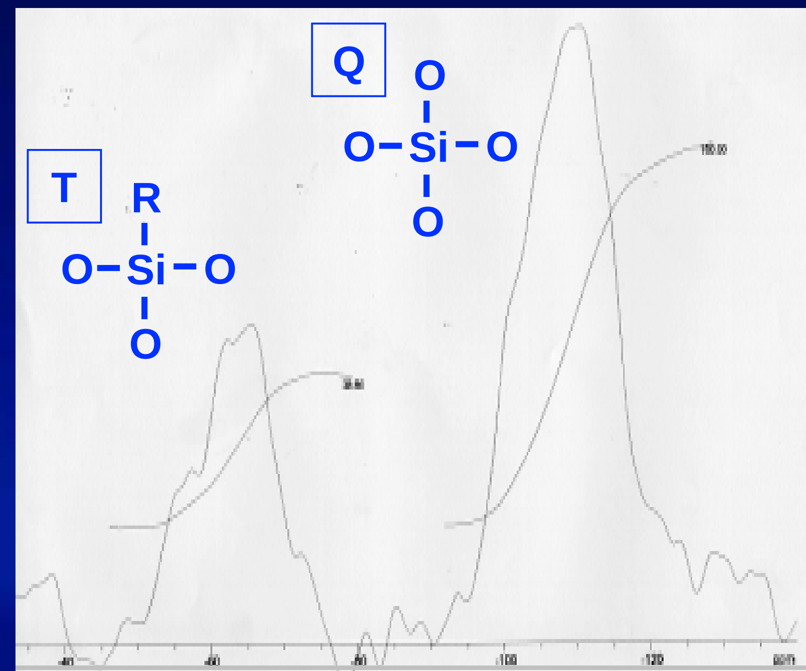


^{29}Si MAS-NMR Supports Cross-Linking

No Treatment

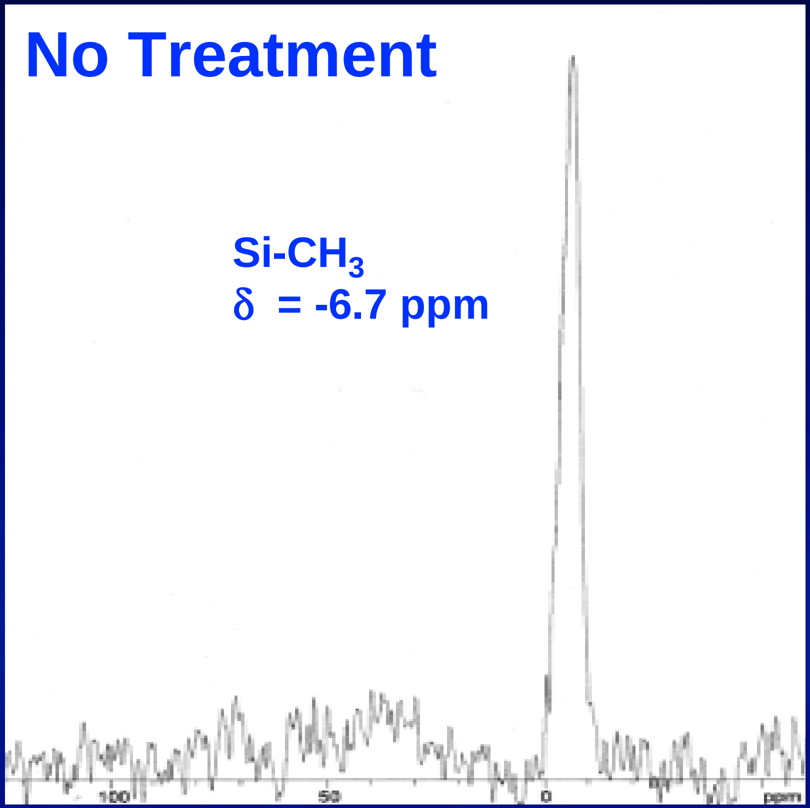


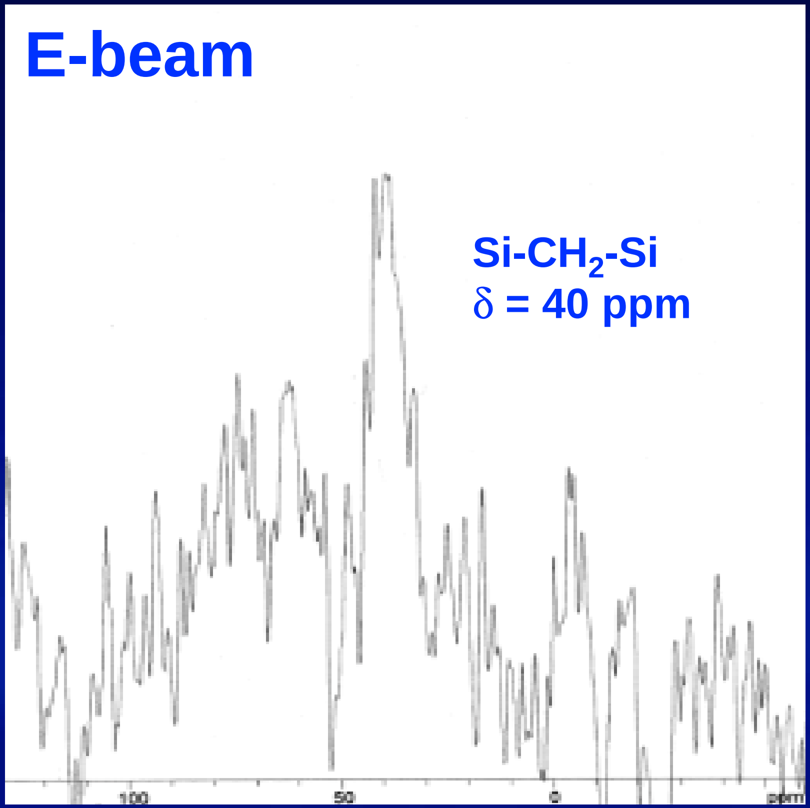
E-beam



T:Q ratio decreases by 50%, supporting a cross-linking mechanism for e-beam treatments

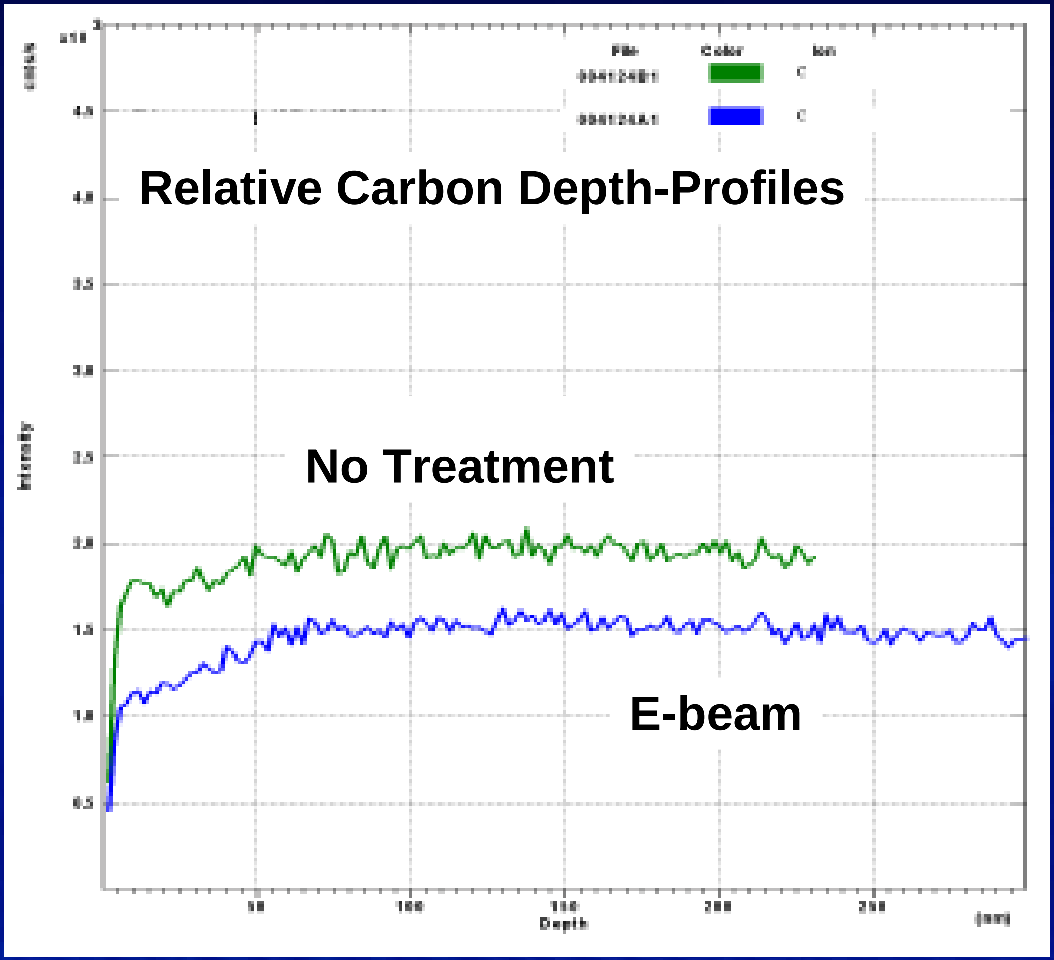
^{13}C MAS-NMR - Methylene Cross-Linking





Cross-linked methylene seen in ^{13}C MAS NMR after e-beam

Carbon Depletion by TOF-SIMS



- Carbon is uniformly depleted by ~ 25% after e-beam
- Contributes to increased dielectric constant

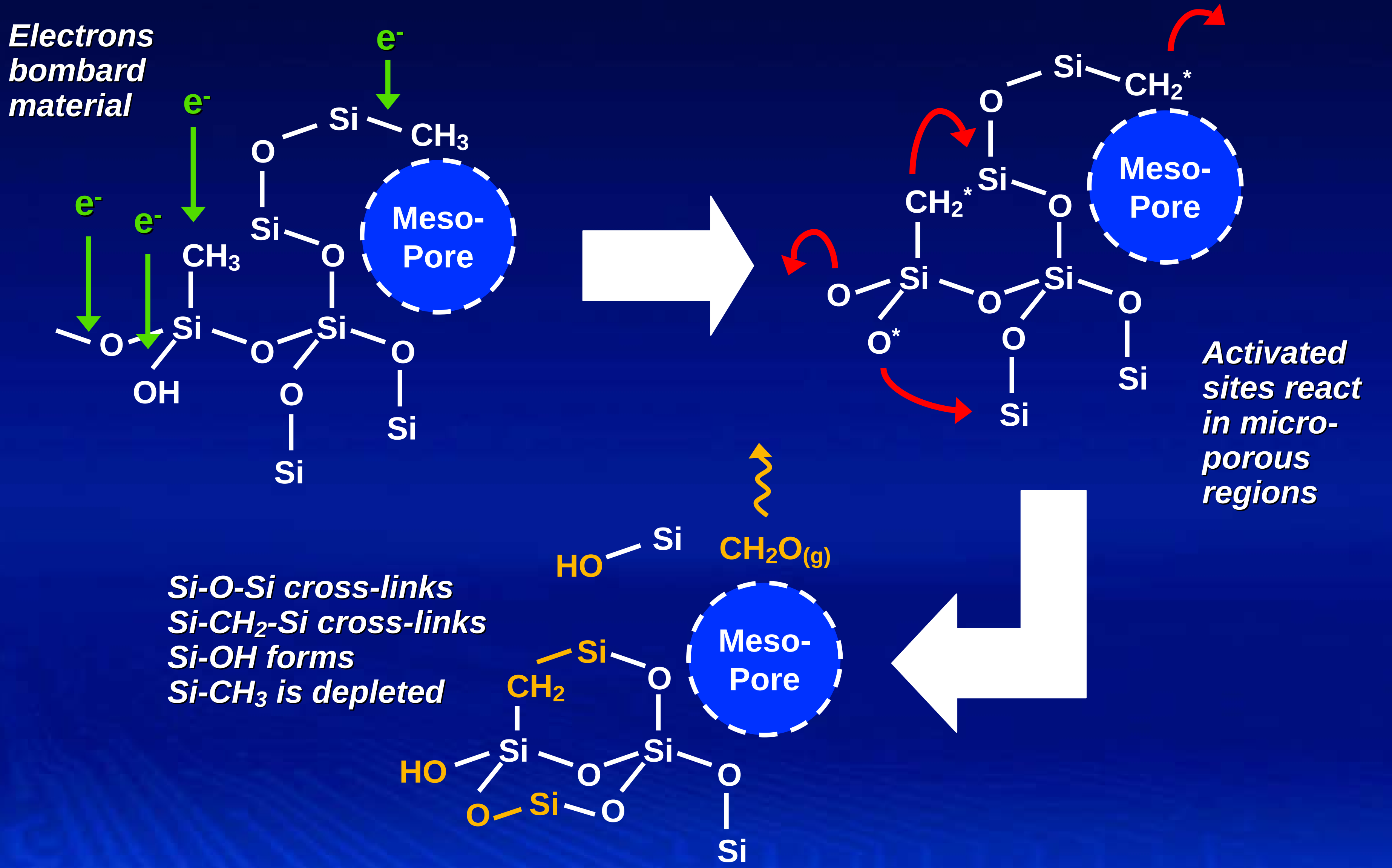
Si-OH Increase by TOF-SIMS

Normalized Ion Intensity

Ion	Mass	No Treatment	E-beam
^{30}Si	29.97	1.00	1.00
$Si\text{-}CH_3$	43.00	3.80	2.56
Si-OH	44.98	1.03	2.33

- Si-OH is not easily detected in FTIR, but TOF-SIMS indicates that its concentration at the surface doubles after e-beam
- It is unlikely that this has a large impact on the bulk properties

Proposed Mechanism



Conclusions

- Adhesion of etch-stop and barrier layers to the ILD was not degraded by porosity – interfacial chemistry appears to drive adhesion more than porosity

- Electron beams improve the modulus and hardness of porous OSG films, with minimal tradeoff in k

- Cross-linking (Si-O-Si, Si-CH_2-Si) is the proposed mechanism for the improved mechanical strength of e-beam treated based on porosity, FTIR, TOF-SIMS and NMR data

Acknowledgments

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